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ORIGINAL ARTICLE

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Scaling or normalising maximum oxygen uptake to predict 1-mile run time in boys

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Abstract There is still considerable debate and some confusion as to the most appropriate method of scaling or normalizing maximum oxygen uptake ($\dot{V}O_{2max}$) for differences in body mass (m) in both adults and children. Previous studies on adult populations have demonstrated that although the traditional ratio standard $\dot{V}O_{2max}$ (ml kg^{-1} min^{-1}) fails to render $\dot{V}O_{2max}$ independent of body mass, the ratio standard is still the best predictor of running performance. However, no such evidence exists in children. Hence, the purpose of the present study was to investigate whether the ratio standard is still the most appropriate method of normalising $\dot{V}O_{2max}$ to predict 1-mile run speed in a group of 12-year-old children ($n=36$). Using a power function model and log-linear regression, the best predictor of 1-mile run speed was given by: speed (m s^{-1}) = $55.1\dot{V}O_{2max}{}^{0.986}m^{-0.96}$. With both the $\dot{V}O_{2max}$ and body mass exponents being close to unity but with opposite signs, the model suggest the best predictor of 1-mile run speed is almost exactly the traditional ratio standard recorded in the units (ml kg^{-1} min^{-1}). Clearly, reporting the traditional ratio standard $\dot{V}O_{2max}$, recorded in the units (ml kg^{-1} min^{-1}), still has an important place in publishing the results of studies investigating cardiovascular fitness of both children and adults.

Keywords Log-linear regression · Maximum oxygen uptake · Power function · Run speed

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Introduction

There has been considerable debate over recent years as to the most appropriate method of scaling or normalizing maximum oxygen uptake ($\dot{V}O_{2max}$) to remove the effects of body mass, in both adults (Astrand and Rodahl 1986; Nevill et al. 1992; Nevill and Holder 1994; Nevill et al. 2003) and children (Welsman et al. 1996; Nevill 1997; Rowland et al. 1999). The consensus of opinion suggests that to facilitate comparisons between groups of different body sizes, the most appropriate way to remove the effects of body mass (m) is to adjust $\dot{V}O_{2max}$ using the power function relationship $\dot{V}O_{2max}=am^{k}$, where a is known as the scaling constant and k is the body-mass scaling exponent. This exponent can be estimated using linear regression analysis after taking logarithms of the power function equation, i.e., $\log_e(\dot{V}O_{2max}) = \log\ a + k\log\ m$. Although there is still considerable controversy as to the theoretical value this exponent should take (e.g., $k=2/3$, 3/4 or $>3/4$) (see Weibel 2002; Nevill et al. 2004), what is now clear is that the traditional ratio standard ($\dot{V}O_{2max}$/mass) fails to remove the effect of body mass and, as such, is inappropriate for epidemiological studies that wish to compare $\dot{V}O_{2max}$ between groups (e.g., active versus inactive individuals) that are not matched on body size.

These conclusions have cast some doubt on the value of reporting the traditional ratio standard $\dot{V}O_{2max}$ recorded in the units (ml kg^{-1} min^{-1}) and its place in publishing the results of studies investigating cardiovascular fitness in both adults and children. However, when investigating a group of recreationally active adults, men ($n=112$) and women ($n=92$), Nevill et al. (1992) were able to confirm that using both $\dot{V}O_{2max}$ (l min^{-1}) and body mass (kg) as predictor variables, the best predictor of 5-km running performance (m s^{-1}) was:

$$\text{Speed}\ \left(\text{m s}^{-1}\right) = 84.3\dot{V}O_{2max}^{1.01}m^{-1.03}.$$

The authors were able to explain why this power function model was both simple and meaningful, i.e. the best predictor of 5-km run speeds was almost exactly proportional to the traditional ratio standard, maximum oxygen uptake (l min^{-1}) divided by body mass (kg) or (ml kg^{-1} min^{-1}). However, as far as we are aware, no study has been able to confirm a similar association between running performance, maximum oxygen uptake and body mass in children. Hence, the purpose of the present article is to investigate whether the ratio standard is still the most appropriate method of normalising $\dot{V}O_{2max}$ to predict 1-mile run speed, assuming that childrens' running performance is an acceptable criterion measure of cardiovasular fitness.

Methods

Participants

Thirty-six circumpubertal boys [mean age 12.2 (0.5) years] participated in a previously published study evaluating the contributions of body composition, maximal aerobic power, and cardiac output to mile run performance (Rowland et al. 1999). In the present report, findings in this investigation were analyzed to determine the empirically-observed allometric relationship between $\dot{V}O_{2max}$, body mass and mile run velocity.

The participants were all healthy and not taking any medication that would affect aerobic performance. To provide for a wide range of fitness, 10 participants were recruited from each quartile of finishers in a 1-mile run test performed as part of school routine fitness testing. Complete laboratory and field testing was completed by only 36 boys, who constitute the basis for this report.

Measurements of puberty and performance

By questionnaire, 14 of the 36 were considered to have entered puberty based on appearance of facial and/or pubic hair. None were considered trained athletes, but two-thirds of the boys had recently competed on community sports teams such as soccer and basketball.

One-mile run testing was performed on a measured outdoor course on a cool day with low humidity. The participants had previous experience with distance running tests, having completed an earlier one-mile run and participated in two sessions of pacing instruction and practice. The one-mile run test, during which the entire group ran simultaneously, was performed after a 10-min stretch and warm up period.

$\dot{V}O_{2max}$ was determined with a continuous progressive cycle testing protocol. Initial and incremental workloads were 25 W with a cycle cadence maintained at 50 rpm. The test was terminated when the participant could no longer maintain this cadence, despite verbal encouragement from the testing staff.

Gas exchange variables were measured using open circuit spirometry with a Q-Plex Cardio-Pulmonary Exercise System (Quinton Instrument, Seattle, Wash., USA). Heart rate was determined electrocardiographically. $\dot{V}O_{2max}$ was defined as the average of the two highest 15-s values in the final minute of exercise. A true exhaustive effort was assumed if participants demonstrated subjective evidence of fatigue (hyperpnea, discomfort) and maximal heart rate rose to >190 bpm and/or maximal respiratory exchange ratio exceeded 1.00.

Procedure and statistical methods

Informed consent and assent was obtained from the parents and children, respectively. This study was approved by the Institutional Review Board of the second author.

The following power function model was used to describe the relationship between VO_{2max} (l min^{-1}) and body mass (m):

$$\dot{V}O_{2max} = a_1 m^k \varepsilon, \quad (1)$$

where a_1 and k are referred to as the scaling constant and scaling exponent, respectively, and ϵ is the multiplicative error ratio. As described above in the introduction, the model can be linearized with a log transformation:

$$\log_e\left(\dot{V}O_{2max}\right) = \log_e(a) + k\ \log_e(m) + \log_e(\varepsilon) \quad (2)$$

and the unknown parameters a and k can be estimated using simple linear regression. In practical terms, this relationship provides the appropriate power-function ratio standard to render $\dot{V}O_{2max}$ independent of m, calculated as the ratio $\dot{V}O_{2max}/m^k$ (see Nevill et al. 1992).

A number of authors (e.g., Jolicoeur and Heusner 1971; Nevill et al. 1992; Nevill and Holder 1994) have explained why, other than for convenience, the log transformation of a model (Eq. 1) is likely to be the most appropriate form to describe such relationships. When the variables $\dot{V}O_{2max}$ and m are plotted against each other, the scores are likely to diverge as both variables increase in size. This feature in data, known as heteroscedasticity, contravenes an important assumption of linear regression, i.e., the error term should remain constant throughout the range of observations. Fortunately, the undesirable characteristic in data, heteroscedasticity, can be corrected using a log transformation, provided the errors ϵ diverge in proportion to the size of the dependent variable, i.e., a proportional or multiplicative error ratio.

We shall assume that the energy required to complete a 1-mile run for 12-year-old boys will be supplied predominantly from aerobic rather than anaerobic sources (i.e., the contribution from anaerobic sources will be negligible). Under such circumstances, run performance recorded as an average speed will be proportional to maximum aerobic power (MAP) or $\dot{V}O_{2max}$ (see di Prampero 2003). In order to establish the most appropriate method of normalizing $\dot{V}O_{2max}$ to best reflect

1-mile run speed, the following power-function model (originally adopted by Nevill et al. 1992) will be used to explore the optimal relationship between 1-mile run speed, $\dot{V}O_{2max}$, and body mass:

$$\text{Run speed}\ \left(\text{m s}^{-1}\right) = a_2 \dot{V}O_{2max}^{k_1} m^{k_2} \varepsilon \qquad (3)$$

where a_2 is a constant and k_1 and k_2 are the exponents likely to provide the best predictor of running speed and as before ϵ is the multiplicative error ratio.

The model can be linearized with a log transformation, and multiple linear regression can be used to estimate unknown parameters a_2, k_1 and k_2. The log-transformed model becomes

$$\begin{aligned}\log_e(\text{run speed}) = \log_e a_2 + k_1 \log_e \dot{V}O_{2max} \\ + k_2 \log_e m + \log_e \varepsilon.\end{aligned}$$

Although not relevant to the present study, the parameter a_2 can be allowed to vary between groups (e.g., boys versus girls), thus conducting a form of analysis of covariance (ANCOVA).

Results

Figure 1 describes the power function the relationship between $\dot{V}O_{2max}$ and body mass. The fitted model (Eq. 1) was found to be $\dot{V}O_{2max} = 0.139m^{0.71}$, with the standard error of estimate (SEE) for the mass exponent $k = 0.712$ being SEE = 0.087, $R^2 = 66.3\%$ ($r = 0.815$) and the error ratio of $s = 0.111$ or 11.7% having taken antilogs.

Evidence of heteroscedasticity can be see in Fig. 1. Further evidence was obtained when the absolute residuals, obtained from fitting a linear model between $\dot{V}O_{2max}$ and m assuming an additive error, were correlated with m resulting in $r = 0.105$. The positive correlation indicates that the residuals tend to diverge with larger m. When the absolute residuals, obtained from fitting the log-linear model (Eq. 2), were correlated with $\log_e m$, the correlation was negligible given as $r = -0.033$, confirming the more appropriate 'constant' error term ($\log_e \epsilon$) in Eq. 2.

The fitted mass exponent was greater that the theoretical parameter, based on the assumption that energy expenditure of humans obeys the surface-area law, i.e., energy expenditure is proportional to $m^{2/3}$ (see Schmidt-Nielsen 1984; Astrand and Rodahl 1986). For comparative purposes only, the theoretical power-function ratio $\dot{V}O_{2max}/m^{2/3}$ for the present sample of 12-year-old boys was 166.58 ($s = 18.0$ ml kg$^{-2/3}$ min^{-1}).

The power-function model relating 1-mile run speed (m s^{-1}) to $\dot{V}O_{2max}$ (l min^{-1}) and m (kg) was given by

$$\text{Run speed}\ \left(\text{m s}^{-1}\right) = 55.1\left(\dot{V}O_{2max}\right)^{0.986}(m)^{-0.96},$$

with both exponents being close to unity but with opposite signs ($k_1 = 0.986$, SEE = 0.1722, and $k_2 = -0.960$ SEE = 0.1506), $R^2 = 55.7\%$ and the error ratio, $s = 0.112$ or 11.9%, having taken antilogs. The best predictor of 1-mile run speed in boys was given by the traditional ratio standard, $\dot{V}O_{2max}$ (l min^{-1}) divided by m (kg) or (ml kg^{-1} min^{-1}) as seen in Fig. 2, i.e. 1-mile run speed is best predicted by $\dot{V}O_{2max}m^{-1}$ (l kg^{-1}). Again, for comparative purposes, $\dot{V}O_{2max}$ expressed 'per body mass' for the present sample of 12-year-old boys was 47.06 ($s = 5.79$ ml kg^{-1} min^{-1}).

Discussion

Clearly, in order to compare physiological variables ($\dot{V}O_{2max}$, lung function and leg power output) between mutually exclusive groups (active versus inactive subjects, smokers versus non-smokers), the confounding effect of age and body size must be removed before valid inference can be made about the benefits of physical activity or the dangers of smoking. Most physiologists now acknowledge that the most appropriate way to adjust $\dot{V}O_{2max}$ to be independent of m is to either divide $\dot{V}O_{2max}$ by m^k, or incorporate body mass as a covariate

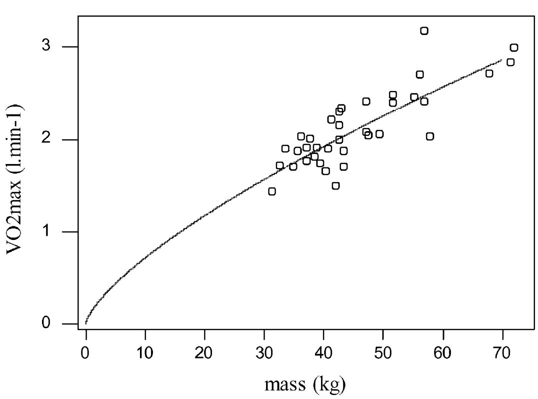

Fig. 1 The power functional relationships between maximum oxygen uptake ($\dot{V}O_{2max}$; l min^{-1}) and body mass (kg) for 12-year-old boys

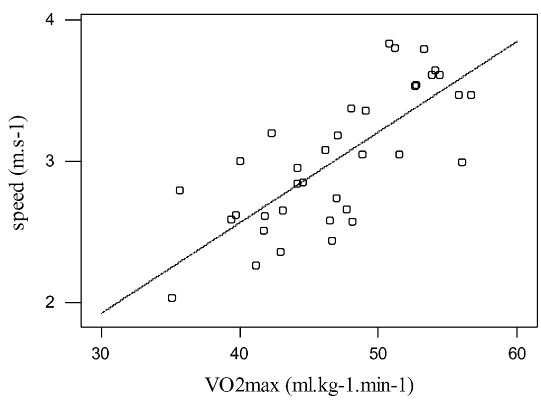

Fig. 2 Running speed (m s^{-1}) versus $\dot{V}O_{2max}$ (ml kg^{-1} min^{-1}) for 12-year-old boys

in an ANCOVA assuming the proportional power function model $\dot{V}O_{2max} = am^k$, where k is the body-mass scaling exponent. When investigating the power function relationship between $\dot{V}O_{2max}$ and body mass of 308 recreationally active adults (men, $n = 179$; women, $n = 129$), Nevill et al. (1992) found no sex differences between the body-mass scaling exponents, but a significant difference was found between the scaling constants. The common body-mass exponent for all 308 adults was $k = 0.67$.

The results from the present study of 12-year-old boys are reassuringly similar to the results obtained using adult participants (Nevill et al. 1992). In order to obtain a measure of $\dot{V}O_{2max}$ that is independent of m, the appropriate body-mass divisor of, or covariate (see Nevill et al. 1992) for $\dot{V}O_{2max}$, was found to be $m^{0.71}$. The fitted mass exponent $k = 0.712$ (SEE = 0.087) was greater than, but not significantly different from, the theoretical surface-area law parameter 2/3. A large number of studies, both human and animal, have reported mass exponents greater than 0.67, often closer to the parameter, 0.75, proposed by Kleiber (1932, 1947). Various authors have attempted to explain these inflated exponents using a variety of different theories, such as the model of elastic similarity proposed by McMahon (1973). However, Heusner (1987) still concludes that "to date there is no biologically satisfactory theoretical explanation of the 0.75 power of mass". However, a recent study by Nevill et al. (2004) confirmed that the proportion of leg muscle mass to body mass was greater than that predicted by geometric similarity, a finding that provides a plausible biological mechanism to explain the inflated exponents ($k > 0.67$) reported in this and numerous other studies investigating the relationship between $\dot{V}O_{2max}$ and m in both adolescent and adults.

For these 12-year-old boys, the optimal $\dot{V}O_{2max}/m$ ratio to predict 1-mile run speed was found to be $\dot{V}O_{2max}{}^{0.986}/m^{0.96}$, almost exactly the traditional ratio standard recorded in the units (ml kg^{-1} min^{-1}). This finding agrees with Nevill et al. (1992), who demonstrated that the optimal ratio to predict 5-km run speed of recreationally active adults was $\dot{V}O_{2max}{}^{1.01}/m^{1.03}$, once again almost exactly the traditional ratio standard recorded in the units (ml kg^{-1} min^{-1}). It is quite remarkable how the empirical results from both these studies confirm the anticipated ratio standard, $\dot{V}O_{2max}$ expressed per unit body mass, as the best predictor of endurance running performance.

In summary, when predicting sporting events that require the performer to carry his or her own body weight, such as running, the body size denominator variable of $\dot{V}O_{2max}$ is likely be the entire body mass (kg). However, further research is required to clarify whether the body size denominator component of $\dot{V}O_{2max}$ in sporting event that are weight supported, such as cycling, wheel-chair racing, rowing or canoeing, is likely to be considerably less, either independent of body mass, ($m^{2/3}$), or absent of body mass, given by unscaled $\dot{V}O_{2max}$ (l min^{-1}).

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